arpa·e

High Efficiency High-Temp Modular Power Workshop
October 19-20, 2017
Washington, D.C.

Opportunities & Challenges for sub-Megawatt & Modular Supercritical Cycles

October 19, 2017

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TharEnergy

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Outline

- Background Thar
- Sub 1 MWe Distributed sCO_2 Power Systems
- Future R&D
- Where Industry is Heading

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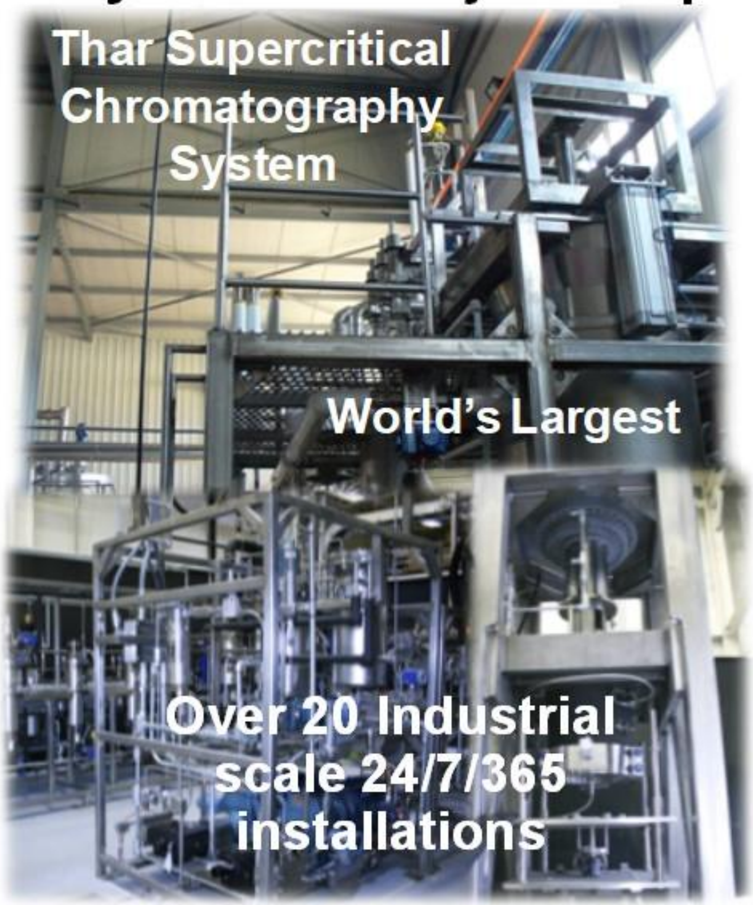
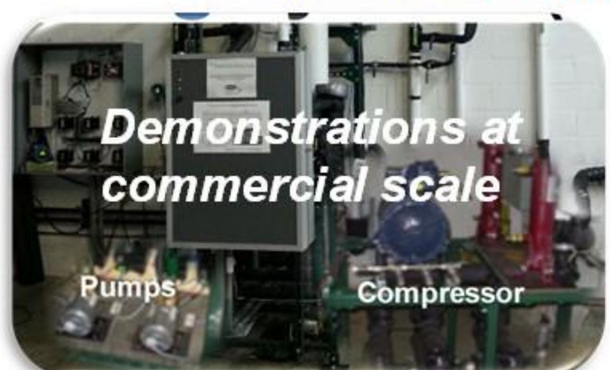
The Thar Brand - Over 25 years of Innovation with "Green" Supercritical Fluid Technologies

Design and commercialization of supercritical systems & major components



Over 5,000 scientific instruments installed

Direct Exchange, R744 (CO_2) Geothermal Heating & Cooling



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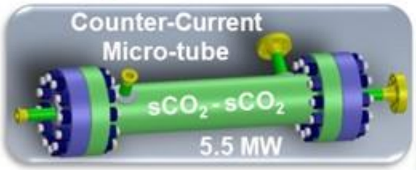
Thar Timeline (cont.)

2014

sCO$_2$ Brayton Power Cycle Development

COMPACT Heat Exchangers for sCO$_2$ Power Cycles



3D Printed, Inconel 718, sCO$_2$-sCO$_2$ Recuperator

ThαrProcess

Design – Construct – Operate Largest GMP sCO$_2$ Extraction System in USA

2015

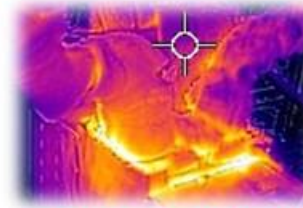
Expands into Liquid Chromatography

Design – Construct – Install Primary Heater for Sunshot One MWe sCO$_2$ Test Loop

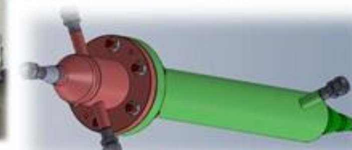
2016

Oxy Combustion Test Facility
Design – Construct – Operate
Demonstrate auto-combustion

Design – Construct – Operate sCO$_2$ Heat Exchanger Test Loop



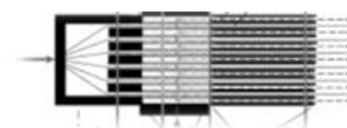
Superior Thermal Performance Confirmed



2017

United States Patent and Trademark Office

Patent - Notice of Allowance
Counter Current Heat Exchanger/Reactor



Thar Pharmaceuticals sold to GRUNENTHAL

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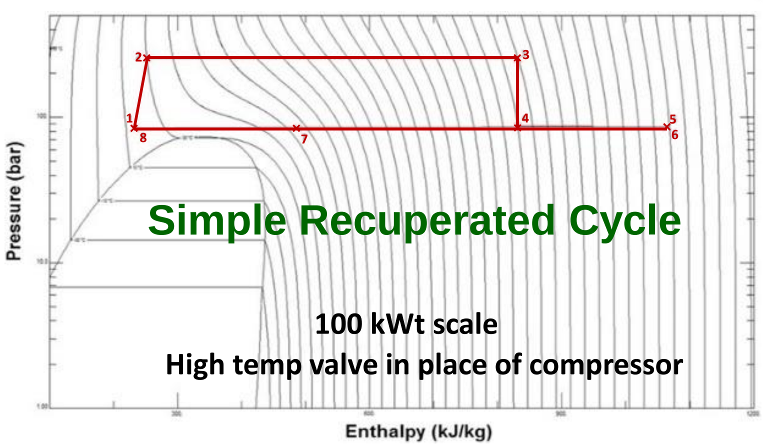
sCO_2 Brayton Power Cycle Heat Exchanger Test Facility

sCO_2 Test Loop Experience

- Operational Performance
- Startup and Shutdown
- Transient Analysis
- Component Performance
  - Pumps
  - Filters
  - Valves
  - Sensors
  - Material properties



Reconfigurable Test Loop

- Pressures to 255 bar
- Temperature to 700°C
- sCO_2 flow to 10 kg/min

Work supported by US DOE NETL under DE-FE0024012 & DE-FE0025348

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What Drives Distributed sCO_2 Power Systems?

- **Performance:** High Efficiency, LCE
- **Operating Cost**
  - Higher efficiency leads to lower operating cost
  - Use of natural gas results in low operating cost
- **Capital Cost:**
  - Market size: ~25,000 units/year
  - Expect capital cost to be <$2000/kW, closer to $1500/kW
- **Size:**
  - sCO_2 systems are small because of:
    - Compact HX, expanders and pumps
    - 1 MW system – designed to easily fit into a 40' container
  - Smaller Package allows for easy installation

What Drives Distributed sCO_2 Power Systems? (cont.)

- **Emissions option:**
  - Oxy-combustion leads little or no emission
- **Air Cooled option:** No water requirement
- **Fuel Flexibility:** Natural Gas, Biomass, Coal
- **Design** to look and feel like a diesel gen-set

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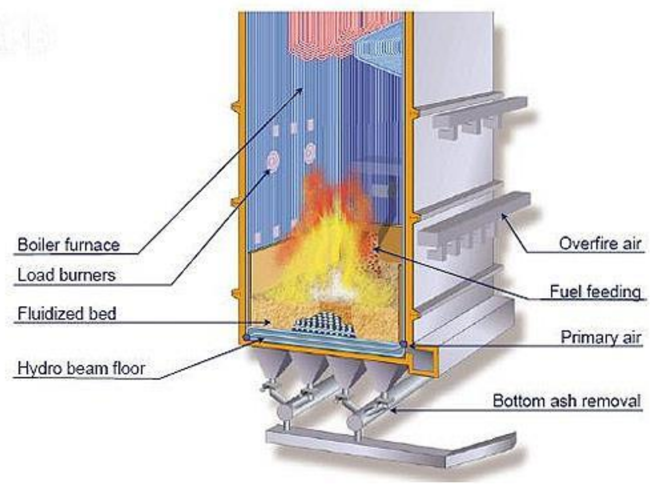
Market Drivers for Distributed Power Systems (< 5 MWe)

Market Drivers

- Deregulation
- Grid Security
- Fuel Availability
- Transmission Cost
- Renewables
- Emissions
- Community Issues

sCO_2 System Focus:
High Efficiency, Modular, Compact Size, Light Weight, Competitively Priced



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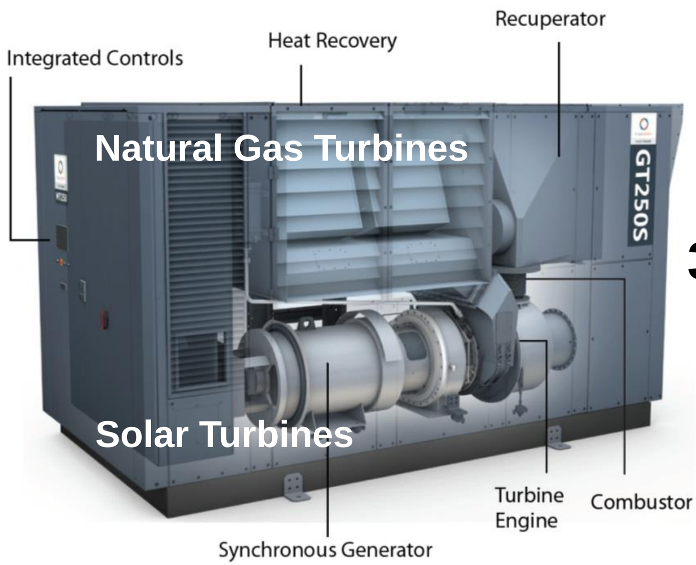
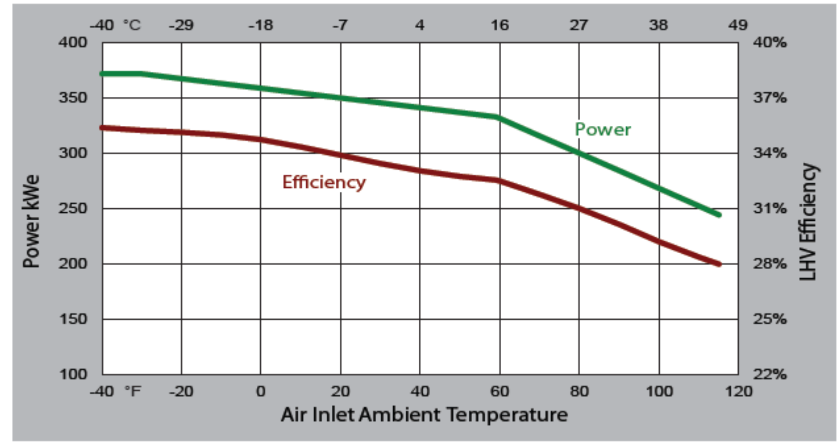
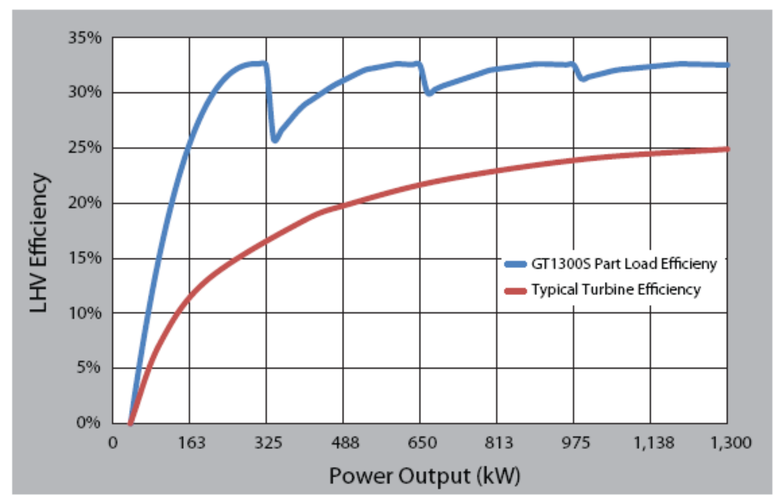
Efficiency and power *change with ambient temperature and system load*



333 kWe



1333 kWe



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Comparison < 1 MWe Distributed Power Systems

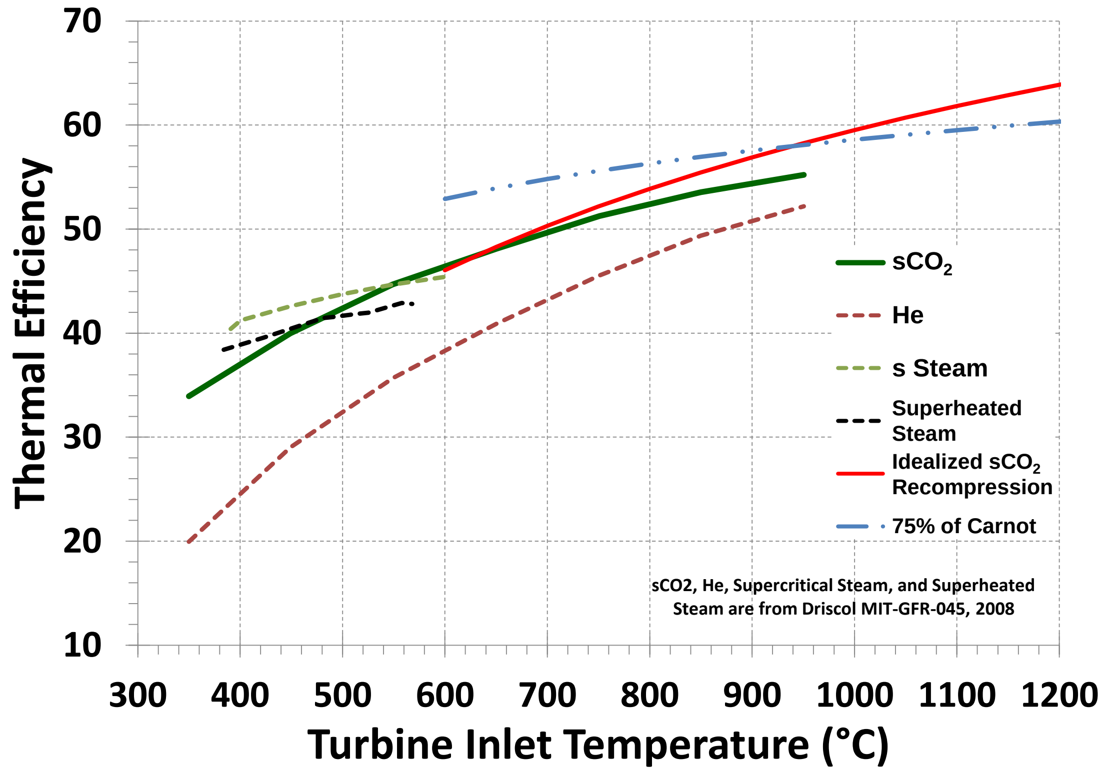
Category	Diesel	Natural Gas	sCO2 Cycle
Efficiency (%)	35 - 37	37 - 39	60
Size (ft3/MW)	4,000 - 6,500	5,800 - 8,000	~3000
Weight (tons/MW)	12.5 - 18	18 - 21	~10
Cost ($/kW)	500	700	~2,000
Commercial	Yes	Yes	Future Design

Volume production and economies of scale are necessary to lower cost so sCO_2 Power Systems can be competitive.

sCO_2 Power Cycle Efficiency

Options to improve cycle efficiency

- Turbine design
- Turbine inlet temperature and pressure
- Recuperator design
- Gas Cooler - air or water cooled
- Fuel source
- Indirect cycle:
  - Oxygen enriched air
- Cycles designed to reduce compression work



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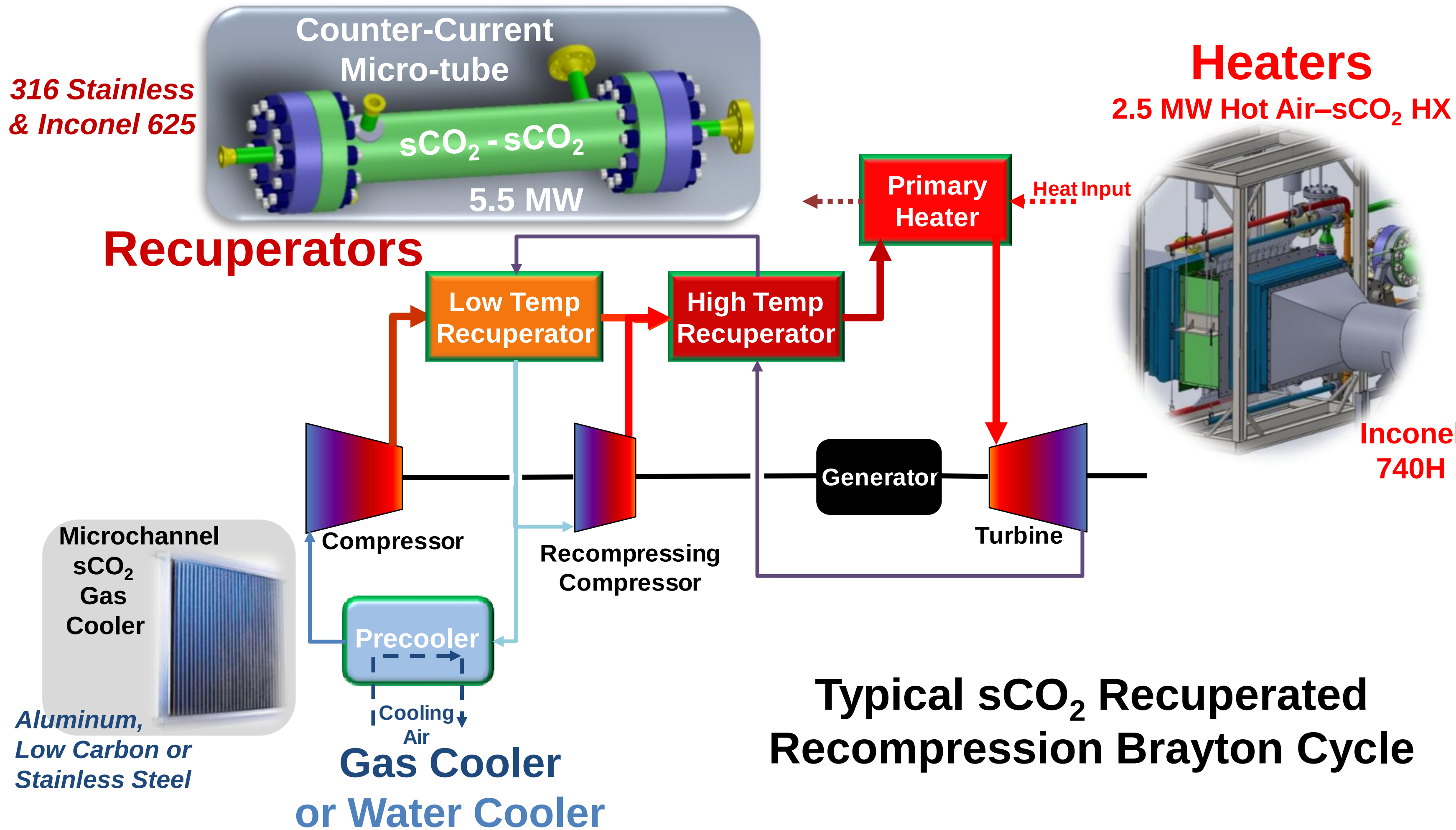
Heat Exchangers are key to improving sCO_2 power cycle efficiency & system costs - sCO_2 Recuperators, Heater HXs & Precooler HXs



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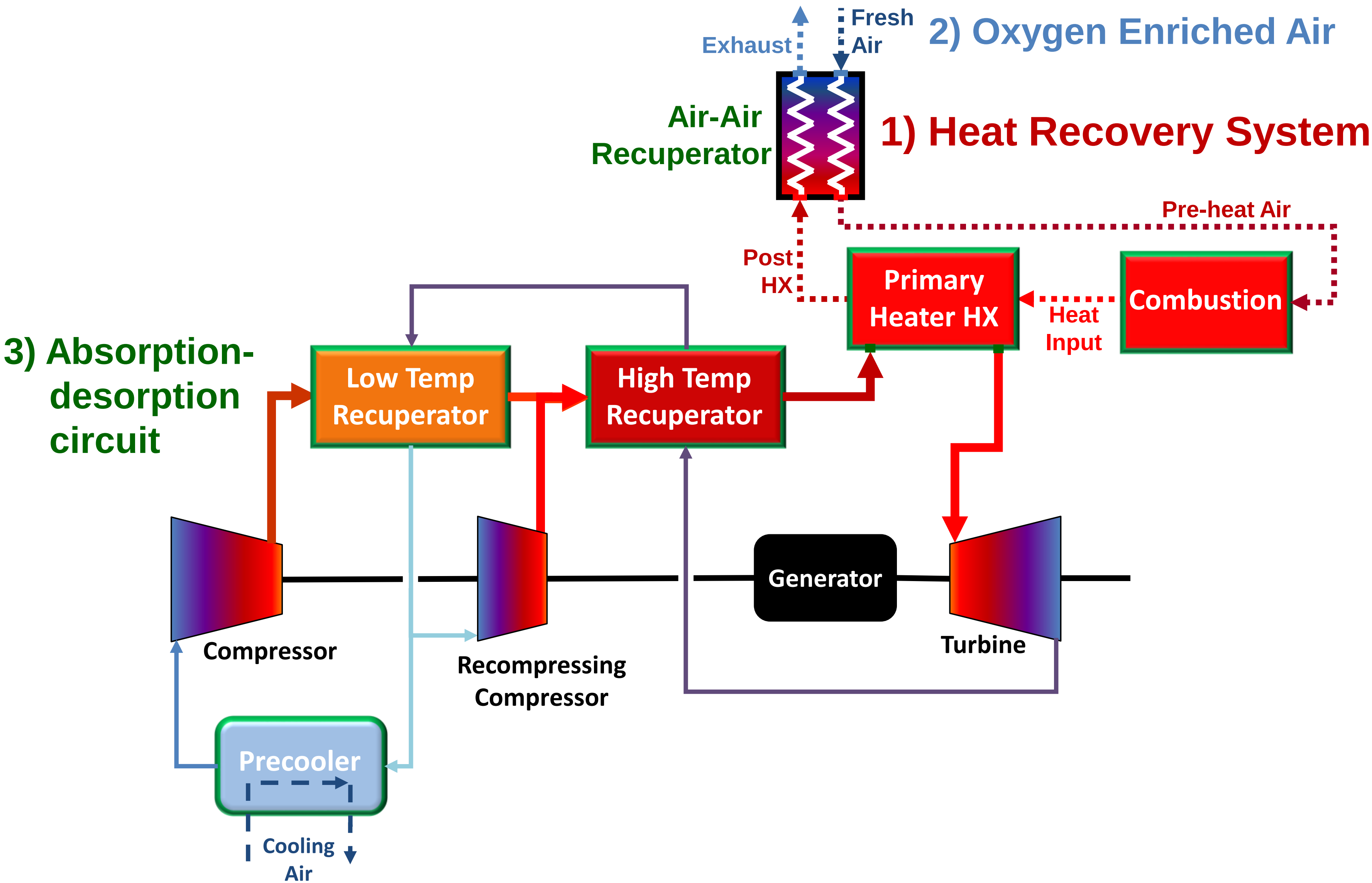
Options to Improve sCO_2 Brayton Power Cycle Efficiency



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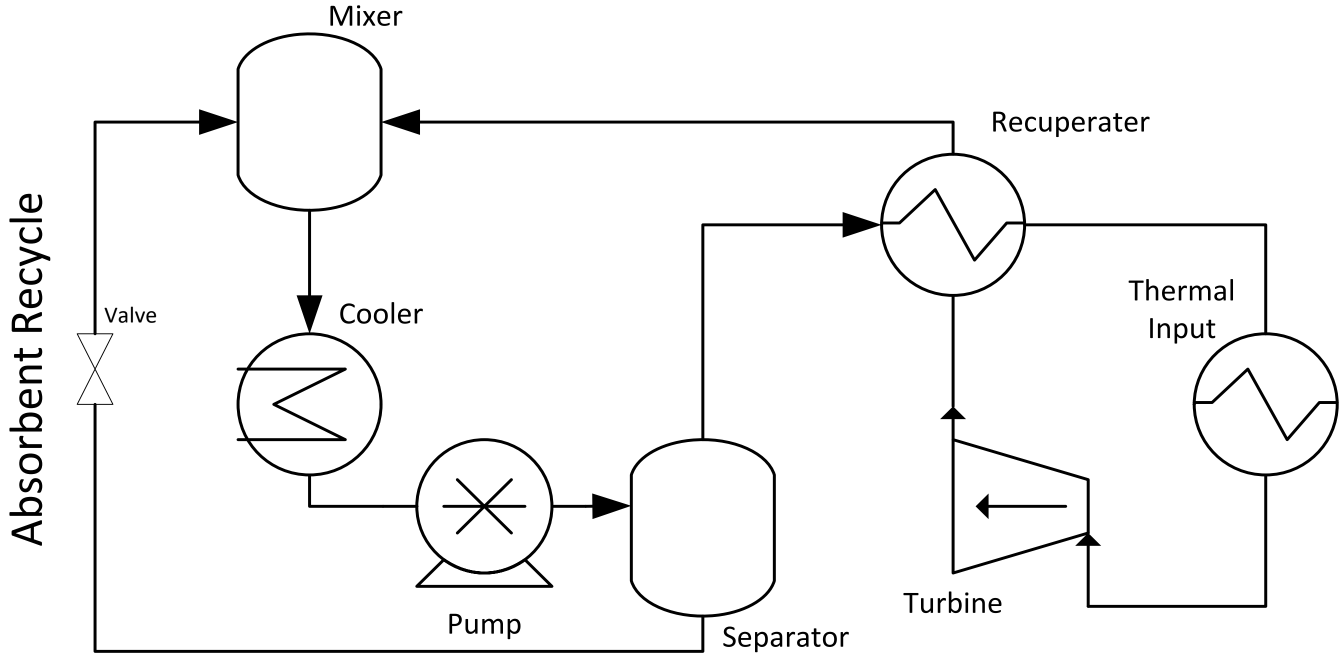
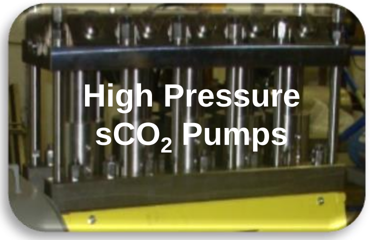
Options to Improve sCO_2 Brayton Power Cycle Efficiency

Absorption/Desorption sCO_2 Brayton Power Cycle

- **Reduce compression work by 40% to 65%**
- **Increase cycle thermal efficiencies by 5-10%**





New Pump Designs

- **Compact and lighter weight**
- **Improve performance two orders of magnitude in same footprint**

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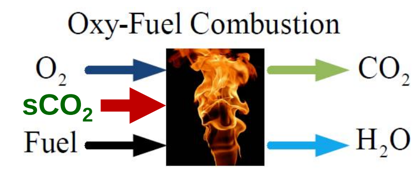
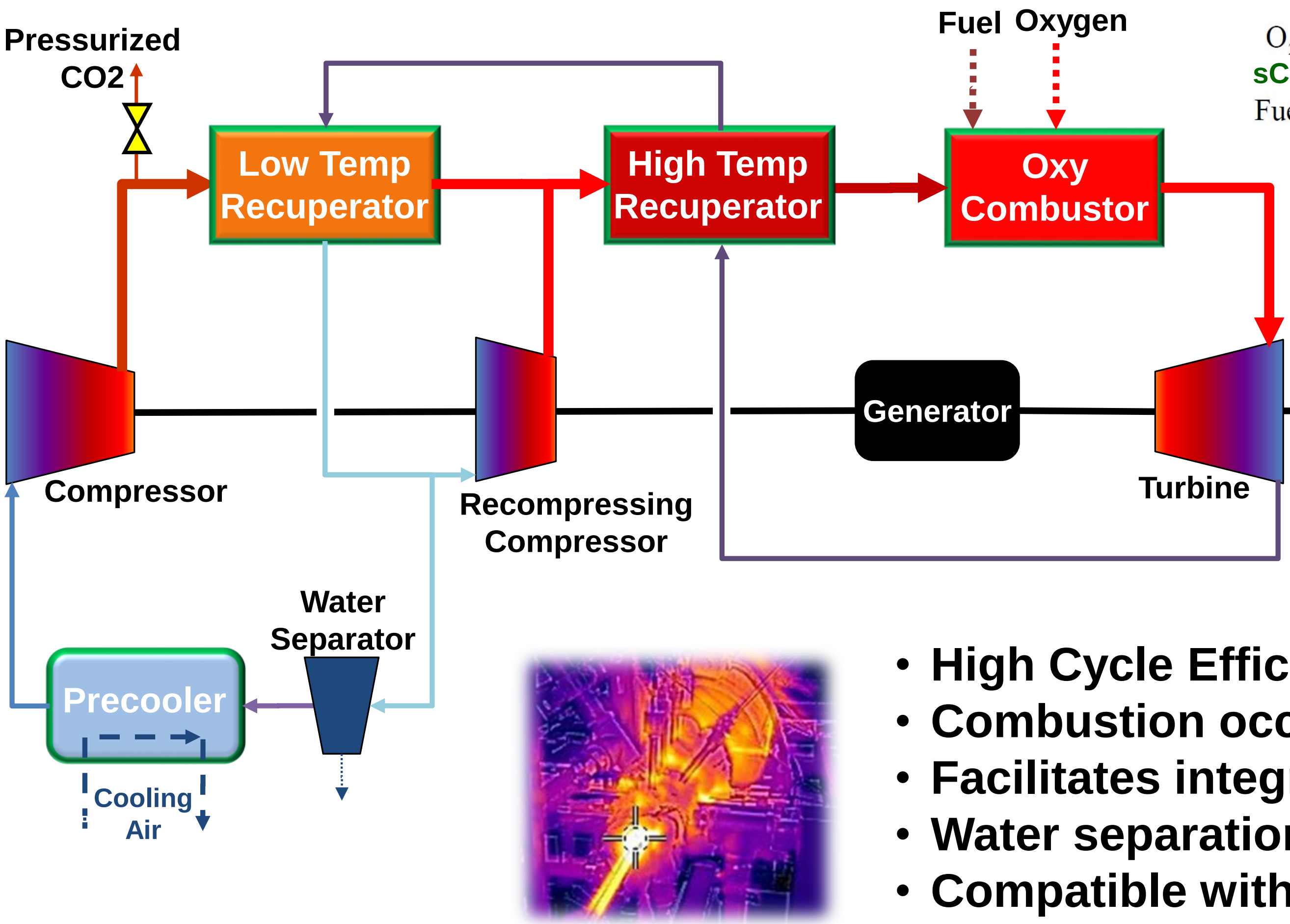
Direct sCO_2 Oxy Combustion Cycle





Demonstrated auto-combustion

- High Cycle Efficiency
- Combustion occurs in the working fluid
- Facilitates integrated carbon capture
- Water separation
- Compatible with dry cooling techniques
- Requires compact and efficient oxygen separation

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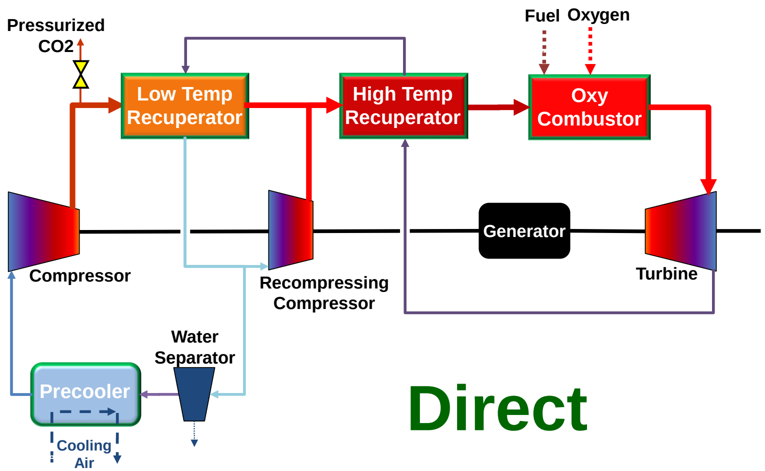
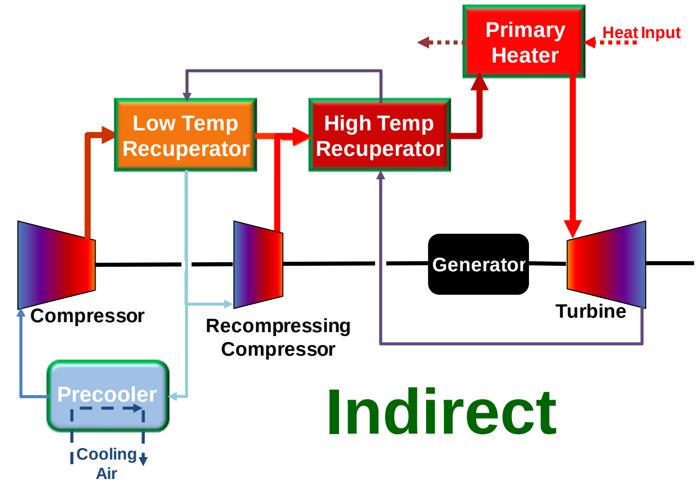
< 1 MWe sCO_2 Distributed Power Systems

Oxy Combustion Power Cycle



Direct

Brayton Power Cycle



Indirect

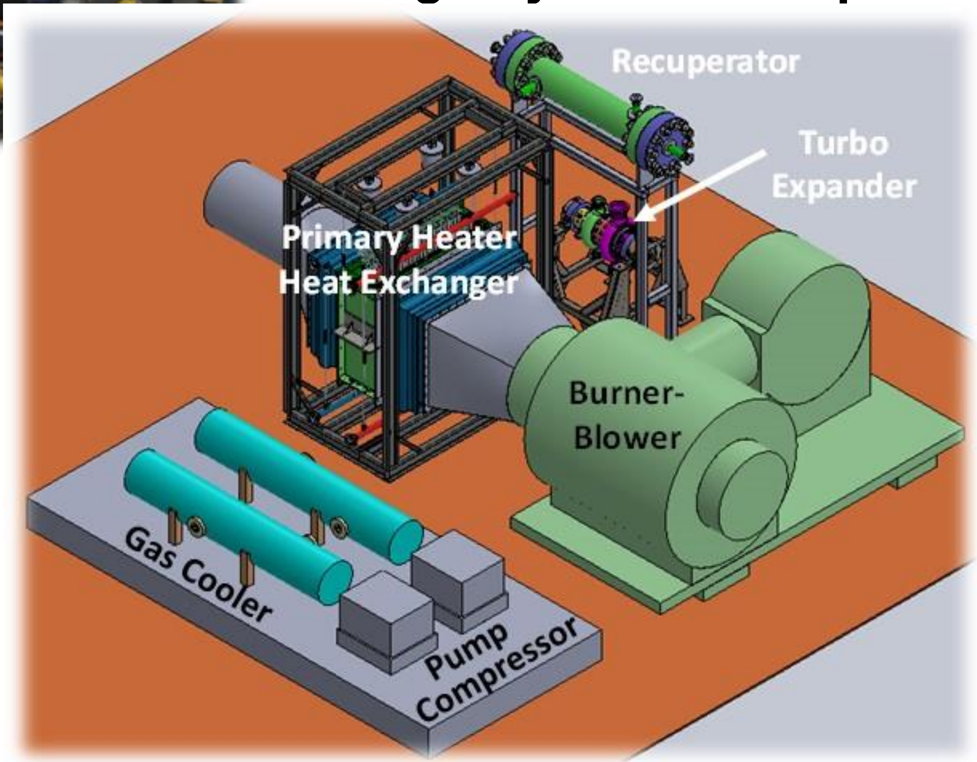
- **Thermal Generation integrated with Electricity Generation**
  - Higher temperatures, >800°C allows for greater efficiencies
  - Collect CO_2: Sell, Use as coolant, or Sequester
  - Higher material costs
  - Requires oxygen source
  - Serious tech gaps

- **Thermal Generation separate from Electricity Generation**
  - Temperatures in the range of 450-700°C
  - Lower temperatures allows the use of commercially available materials
  - Fuel Flexibility: Natural Gas, Coal, Biomass
  - Unable to collect CO_2

1 MWe sCO_2 Brayton Power System

For <1 MWe systems, rotating expanders are a problem. Consider reciprocating expanders.

Package System Example



Major Components

- 2 Recuperators HX
- 1 Primary Heater
- 1 Condenser HX
- 2 Compressors
- 1 Expander

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Future R&D

- **Pressurized Oxygen Generation:**
  - Membrane (high compression cost), Cryo (not cost efficient for small system), High pressure high temp electrolysis
- **Expanders:**
  - Rotating expanders are not efficient for small scale systems
    - ❖ High rpms require gear reduction, reducing efficiency and increasing cost
  - Simple highly efficient reciprocating expanders
- **Reciprocating Expanders/compressors:**
  - Integrating the expander and the pump/compressor
  - Improved seals to reduce size and cost
- **Controls**
  - Understanding system behavior, so controls can be developed for normal operation and startup and shutdown
- **Advanced Manufacturing: 3D Printing of Components**
  - Ability to print long sections
  - Need to use less expensive metal powders

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Where Industry is Heading

- **sCO_2 is better served by focusing on:**
  - **Small distributed power generation systems**
    - For large commercial buildings, small industries, grid stability
    - Lower operating cost will be a big driver for this market
  - **Direct oxy-combustion using natural gas**
    - Byproduct can generate additional income by converting high pressure CO_2 into other products such as plastics.
  - **Indirect cycle has a huge advantage due to the feedstock**
    - **Market size: Diesel Generators to exceed $20B in 2020**
      - **Growing at 5.4% every year**
    - **Key Players: Caterpillar, Cummins, Generac, Kohler**
    - **Fastest growing segment: Asia**

Questions and Discussions!!!

- Thank You

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